STRUCTURAL GEOLOGY

An Introduction to Geometrical Techniques

Third Edition

DONAL M. RAGAN

Department of Geology Arizona State University

JOHN WILEY & SONS, INC.

New York Chichester Brisbane Toronto Singapore

Copyright @ 1968, 1973, 1985 by John Wiley & Sons, Inc.

All rights reserved. Published simultaneously in Canada,

Reproduction or translation of any part of this work beyond that permitted by Sections 107 and 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful. Requests for permission or further information should be addressed to the Permissions Department, John Wiley & Sons.

Library of Congress Cataloging in Publication Data:

Ragan, Donal M. Structural geology.

Includes index.

1. Geology, Structural. I. Title.

QE601.R23 1984 551.8 84-19658 ISBN 0-471-08043-8

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Contents

1. Attitude of Planes 1

- 1.1 Introduction 1
- 1.2 Definitions 1
- 1.3 Dip and Strike 1
- 1.4 Graphic Methods 4
- 1.5 Finding Apparent Dip 8
- 1.6 Finding True Dip and Strike 11
- 1.7 Accuracy of Dip and Strike Measurements 15

2. Thickness and Depth 19

- 2.1 Definitions 19
- 2.2 Thickness by Direct Measurement 19
- 2.3 Thickness by Indirect Measurement 20
- 2.4 Thickness Between Non-Parallel Planes 23
- 2.5 Depth to a Plane 26
- 2.6 Distance to a Plane 27
- 2.7 Measurement Errors 28

3. Structural Planes and Topography 33

- 3.1 Exposures on Horizontal Surfaces 33
- 3.2 Exposures in Areas of Topographic Relief 35
- 3.3 Dip and Strike from Geologic Maps 38
- 3.4 Three-Point Problem 39
- 3.5 Predicting Outcrop Patterns 40

4. Lines and Intersecting Planes 45

- 4.1 Definitions 45
- 4.2 Linear Structures 45
- 4.3 Plunge of a Line 46
- 4.4 Apparent Plunge 47
- 4.5 Pitch of a Line 49
- 4.6 Intersecting Planes 52
- 4.7 Accuracy of Trend Determinations 55

5. Graphic Solutions with the Stereonet 59

- 5.1 Stereographic Projection 59
- 5.2 Techniques of Plotting 63
- 5.3 Attitude Problems 68
- 5.4 Rotations 72
- 5.5 Rotational Problems 75
- 5.6 Dip and Strike Errors 79
- 5.7 Intersection Errors 80

6. Faults 85

- 6.1 Definitions 85
- 6.2 Fault Classification 86
- 6.3 Translational Faults 92
- 6.4 Fault Terminations 96
- 6.5 Rotational Faults 97
- 6.6 Overthrusts 98
- 6.7 Folds and Faults 103
- 6.8 Extensional Faults 104

7. Stress 111

- 7.1 Introduction 111
- 7.2 Surface Tractions 111
- 7.3 Stress Components 113
- 7.4 Stress in Two Dimensions 115
- 7.5 Mohr Circle for Stress 120
- 7.6 Effects of Pore Fluid Pressure 126
- 7.7 Tractions versus Forces 127

8. Faulting and its Causes 129

- 8.1 Introduction 129
- 8.2 State of Stress at Depth 129
- 8.3 Experimental Fractures 130
- 8.4 Amonton's Law 131
- 8.5 The Coulomb Criterion 133
- 8.6 Classification of Faults 134
- 8.7 Faults and Stresses 135
- 8.8 Magnitudes of the Stress Components 140
- 8.9 Faults in Anisotropic Rocks 144
- 8.10 Limitations 146

9. Concepts of Deformation 149

- 9.1 Introduction 149
- 9.2 Card-Deck Models 150
- 9.3 Homogeneous Deformation by Simple Shear 151
- 9.4 Analysis of Simple Shear 153
- 9.5 Superimposed Deformations 156
- 9.6 Deformed Pebble Problem 159
- 9.7 Inhomogeneous Deformation 164
- 9.8 Motion Leading to Deformation 166

10. Strain in Rocks 175

- 10.1 Introduction 175
- 10.2 Simple Strain Analysis 175
- 10.3 Geometry of the Strain Ellipse 177
- 10.4 Mohr Circle for Finite Strain 183
- 10.5 Solving Problems with the Mohr Circle 186
- 10.6 Strain Ellipse from Measured Extensions 189
- 10.7 Strain Ellipse from Measured Angles 195
- 10.8 Rotation 199

11. Description and Classification of Folds 201

- 11.1 Introduction 201
- 11.2 Description of Single Surfaces 201
- 11.3 Relationships between Adjacent Surfaces 205
- 11.4 Isogon Classification 208
- 11.5 Fold Orientation 209
- 11.6 Associated Structures 213
- 11.7 Noncylindrical Folds 216

12. Parallel Folds 219

- 12.1 Introduction 219
- 12.2 Parallel Folds in Cross Section 221
- 12.3 Balanced Cross Sections 228
- 12.4 Depth of Folding 232
- 12.5 Kink Bands and Chevron Folds 235
- 12.6 Nonparallel Folds 238

13. Similar Folds 243

- 13.1 Introduction 243
- 13.2 Geometry of Shear Folding 243
- 13.3 Superposed Folds in Two Dimensions 248
- 13.4 Wild Folds 252
- 13.5 Superposed Folds in Three Dimenions 253
- 13.6 Folds in Shear Zones 255

14. Folds and Topography 257

- 14.1 Map Symbols for Folds 257
- 14.2 Outcrop Patterns 257
- 14.3 Down-Plunge View of Folds 259
- 14.4 Fold Profile 262
- 14.5 Attitude of the Hinge Surface 267

15. Structural Analysis 269

- 15.1 Introduction 269
- 15.2 S-Pole and Beta Diagrams 269
- 15.3 Fold Axis and Axial Plane 270
- 15.4 Equal-Area Projection 272
- 15.5 Contoured Diagrams 274
- 15.6 Interpretation of Diagrams 277
- 15.7 Superposed Folds 280
- 15.8 Sampling Problem 282

16. Linear and Planar Structures in Tectonites 287

- 16.1 Introduction 287
- 16.2 Isotropy and Homogeneity 287

- 16.3 Analysis of Planar and Linear Fabrics 288
- 16.4 Complex Structures 292
- 16.5 L-S Tectonites 294

17. Drill Hole Data 297

- 17.1 Introduction 297
- 17.2 Attitude of a Plane from an Oriented Core 297
- 17.3 One Drill Hole Intersecting a Plane 299
- 17.4 Circles in Stereographic Projection 304
- 17.5 Stereographic Solution of the Two Drill Hole Problem 307
- 17.6 Analytical Solution of the Two Drill Hole Problem 310
- 17.7 Three Drill Holes 311
- 17.8 Interpretation of Folds 313

18. Structural Contours 317

- 18.1 Introduction 317
- 18.2 Contouring 317
- 18.3 Form Line Contours 322
- 18.4 Isopach and Isochore Maps 324

19. Maps and Cross Sections 327

- 19.1 The Geologic Map 327
- 19.2 Other Types of Maps 330
- 19.3 Geologic History 331
- 19.4 The Structure Section 332
- 19.5 Other Types of Sections 336
- 19.6 Vertical Exaggeration 336

20. Block Diagrams 343

- 20.1 Introduction 343
- 20.2 Orthographic Net 344
- 20.3 Unit Cube 344
- 20.4 Geologic Structure 347
- 20.5 Topography 348
- 20.6 Modified Blocks 350

Appendices

A. Elements of Descriptive Geometry 353

- A.1 Introduction 353
- A.2 Orthographic Projection 353
- A.3 Graphic Solutions 355
- A.4 True Length of a Line 356
- A.5 Normal View of a Plane Figure 359

B. Spherical Trigonometry on the Stereonet 361

- B.1 Introduction 361
- B.2 Right-spherical Triangles 361
- B.3 Oblique-spherical Triangles 366

References 371

Author Index 385

Subject Index 389